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A SYSTEMATIC ASSESSMENT OF INDIANA MAMMAL RESEARCH, RESEARCHERS, AND FUTURE NEEDS

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ABSTRACT. No systematic review has been conducted or centralized repository created for published research on wild mammals in Indiana, despite studies dating back two centuries. I conducted a systematic review in Web of Science™, which produced 714 research articles on wild Indiana mammals published in 156 outlets by 1131 authors since 1906. Thirty-one authors published $\geq$ 10 articles, and 29 papers were cited $\geq$ 100 times. The most frequently used outlet was Proceedings of the Indiana Academy of Science (n = 155). Most studies dealt with ecology or natural history (38.2%) and management (22.0%). Indiana myotis (*Myotis sodalis*) was the most frequent target of study, and bats ranked as 6 of the top 10 most-studied species. Cold spots, i.e., understudied species $\times$ discipline combinations that might merit increased future attention, were assessed using quantile analysis of chi-square residuals and normalized metrics of research effort. Understudied state species of current conservation concern included star-nosed mole (*Condylura cristata*), badger (*Taxidea taxus*), swamp rabbit (*Sylvilagus aquaticus*), Franklin's ground squirrel (*Policocitellus franklinii*), and least weasel (*Mustela nivalis*), with population declines suspected in the latter. Understudied nonlisted furbearers for which range-wide population declines have been documented included gray fox (*Urocyon cinereoargenteus*) and muskrat (*Ondatra zibethicus*). Cold spots for nongame, nonlisted species included *Cryptotis* and *Sorex* shrews and southern bog lemming (*Synaptomys cooperi*). This single digital source for the widely scattered primary literature on Indiana mammals should make the voluminous prior research more accessible and useful to scientists planning future studies.

Keywords: bibliometrics, hotspot analysis, literature review, mammalogy

INTRODUCTION

Knowledge of mammalian biology is key to the successful management and conservation of mammals, and knowledge is most reliably derived from scientific investigation. The Indiana Department of Natural Resources (IDNR) technical advisory committee on mammals relies on expertise and familiarity with scientific studies to provide recommendations pertaining to mammal conservation in Indiana. The committee incorporates data and findings from diverse sources to inform its deliberations, and the monograph "Mammals of Indiana" (Whitaker & Mumford 2009) serves as an important source because it provides accounts of each species, with a focus on ecological attributes often relevant to species conservation.

Notwithstanding the impact of the monograph by Whitaker & Mumford (2009), no systematic review has been conducted or centralized repository created for publications in the primary literature on mammal studies in Indiana. Such a resource could serve generally as an aid to scientists planning new research on Indiana mammals and specifically could facilitate more informed recommendations from the IDNR technical advisory committee on mammals. Consequently, a systematic review of research on mammals in Indiana was conducted. It relied on databases containing > 34,000 journals and > 2 billion cited references (Muren 2021). The overarching goals were to characterize the status of scientific studies on Indiana mammals, and the contributions of scientists undertaking these studies. More specific objectives were to 1) create a digital repository of published research on wild Indiana mammals; 2) assess the disciplinary and taxonomic focus of past research; 3) conduct a nonspatial analysis of hot and cold spots (e.g., Barthel et al. 2015) to identify research inequities as an aid when setting priorities for future work; and 4) assess scientists contributing to research on Indiana mammals including bibliometric indexes of their impact and productivity.

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METHODS

Systematic review.—Web of Science™ keyword searches were conducted 19–21 May 2022

Table 1.—Research disciplines used to classify the focus of research publications on wild Indiana mammals. A publication could address > 1 discipline.

Discipline	Description
Behavior	Response of an individual mammal or group to environmental stimuli
Ecology	Study of mammals and their environment including natural history
Survey	Range records, geographic distribution, or occurrence surveys
Management	Biodiversity protection, restoration, consumptive use of game species, mitigation of problems, or to understand responses to humans and land use
Parasites/Disease	Study of mammalian parasites, diseases, and toxins
Genetics	Study of genes, genetic variation, heredity including phylogeography
Paleontology	Study of mammals and associates of the geologic past
Physiology/Morphology	Study of form, functions, or mechanisms within an organism including development and histology
Taxonomy/Systematics	Describing, classifying, and naming mammals; also, phylogenetic diversity and relationships of mammals

using all databases available. Searches were conducted using two search strings (details in Supplemental Material, at https://www.indianaacademyofscience.org/publications/proceedings). The first search extracted journal or proceedings articles and book chapters combining the keyword "Indiana" and a set of class, ordinal, genus, and common name descriptors for mammals in the state. Topics related to medicine and psychology were excluded, and the search was refined to focus on 10 relevant research areas. The second search relied on the same set of taxonomic terms but did not use Indiana as a keyword. Instead, it used address affiliations for institutions of higher education in Indiana and excluded from consideration articles appearing in journals for which odds of publication of mammal research were deemed nil (e.g., Lancet, Journal of Human Evolution, or Archives of Internal Medicine). Weekly updates to add recent publications were conducted through 29 December 2022 using the Web of Science™ alerts service.

Records from searches were inspected, and extraneous publications on topics other than wild Indiana mammals were culled. The remaining records were merged into a marked list containing each publication's bibliographic information, abstract (if available), and citation frequency. Marked lists were merged, exported to a spreadsheet, and inspected again for extraneous or duplicate records. The spreadsheet was then circulated to members of the IDNR technical advisory committee on mammals for comment and refinement.

Based on inspection of the title, abstract, and occasionally the full article, each record in the spreadsheet was classified according to its focal species and research discipline(s). Thus, the records yielded a 60 species $\times$ 9 disciplines contingency table. The list of focal Indiana mammals coincides with the list maintained by the state's mammalogist (https://www.in.gov/dnr/fish-and-wildlife/nongame-and-endangered-wildlife/mammals/mammals-list/) in conjunction with taxonomic revisions provided by the American Society of Mammalogists Mammal Diversity Database (https://mammaldiversity.org). The nine research disciplines (Table 1) were behavior, ecology, distribution, genetics, management, paleontology, parasites or disease, physiology or morphology, and taxonomy or systematics. Species-level scoring was not done for 18 studies with a focus on methods applicable to general groups of species (e.g., Whitaker 1988; Whitaker et al. 2009), 36 with a focus on prehistoric or non-native species (e.g., Woodman & Branstrator 2008; Webster et al. 2019), and 28 surveys not focused on particular species (e.g., Veilleux et al. 1999; Karns et al. 2006). Species also were classified qualitatively into three abundance classes: abundant, common, or of conservation concern. These classifications were derived from results in Knapp et al. (2003), supplemented and updated to reflect known changes in listing status or suspected changes in abundance over the past two decades. Species were further classified based on their status as game species and their current state and federal listing designation.

Statistical analysis.—To test whether status as either i) game species or ii) listed species (i.e., federally threatened or endangered, state endangered, or state species of special concern) affected mean fraction of published research devoted to a species, a two-way analysis of variance was conducted. To test for trends in disciplinary focus, the annual probability of occurrence of a paper addressing each discipline was modeled separately with logistic regression (logit link) using year and number of publications in that year as covariates. Irrespective of species, the fraction of all research focused on each discipline was computed to identify areas in which research was concentrated. Likewise, the fraction of research devoted to each species was computed, irrespective of discipline. Chi-square goodness-of-fit tests were conducted to test the null hypotheses of equal disciplinary and species representation in published research.

Two approaches were used to assess inequities in research focus, i.e., hot and cold spots in the relative frequency with which studies were conducted on species × discipline combinations. First, a chi-squared test of homogeneity of proportions for the 60 × 9 table was conducted. A quasi-*p* value was computed under an assumption of fixed marginal row and column totals using 5000 Monte Carlo resampling trials. Species by discipline bubble maps were generated based on the Pearson chi-square residuals, with bubble area proportional to the focal species × discipline distance from the median residual value. Thus, the most extreme percentiles of residuals were depicted with the largest bubbles. Pearson residuals below the 0.025 and 0.05 quantiles were identified to highlight, respectively, "cold and cool spots", i.e., species that were understudied in a discipline relative to the overall distribution of research. Similarly, species with residuals above the 0.975 and 0.95 quantiles were identified to highlight, respectively, "hot and warm spots", i.e., species receiving a disproportionate amount of research attention in a discipline relative to the overall distribution of research.

A second, simpler method of cold spot analysis focused on interspecific comparisons of research for each discipline separately. Species results were sorted for the five most-studied disciplines and expressed as a fraction of the maximum study score in each discipline. Research-deficient species were defined as those listed and harvested species with < 5% (cold spots) or 5–10% (cool spots) of research attention relative to the most-studied species in a discipline. Species-level analysis results excluded non-native commensals *Rattus norvegicus* and *Mus musculus* in tables and figures.

Bibliometric analysis.—Numerous measures have proliferated to index research contributions by scientists. Collectively referred to as bibliometrics, such measures have become popular because they attempt to express performance in convenient currencies (Wildgaard et al. 2014). For each author and coauthor of at least one paper on Indiana mammals, a tally was made of the number of publications, the total number of citations of the published papers, and the *h*-index, defined as the number of publications produced with at least *h* citations each (Hirsch 2005). Since these metrics tend to increase with time spent as a researcher (Swihart et al. 2016, 2018), annual publication and citation rates were also computed. The latter computation used the first and last years in which an author published on Indiana mammals. Citation rate used the interval from 2022 to the year of the first publication. An annual rate of *h*-index accumulation, known as the *m* quotient (Hirsch 2005), was also computed using the elapsed years from 2022 to the year of first publication. All analyses were conducted in R version 4.2.1 (R Core Team 2022).

RESULTS

The systematic review revealed 714 papers published on Indiana mammals since 1906, beginning with a paper describing mammalian remains in Donaldson cave (Hahn 1906a). Articles were published in 133 journals and 23 other scientific outlets. Proceedings of the Indiana Academy of Science was the most frequently used outlet, with 155 (22.0%) of the total publications, followed by Journal of Mammalogy with 83 (11.6%). Fewer than five articles were published annually before 1960, after which publication rate generally increased, to > 15 per year during the 21st century (see Figure in Supplemental Material).

Patterns in mammal research.—From a content perspective, research on Indiana mammals has not been homogenously distributed among disciplines (X^2 = 2993, df = 8, $p <$ 0.000001). Specifically, research has focused primarily on ecology and natural history (38.2% of topics studied), followed by conservation and management (22.0%), parasitology and disease (15.5%), behavior (11.6%), and survey studies documenting distribution

(6.8%). Physiology (2.8%), genetics (1.6%), taxonomy and systematics (0.9%) and paleontology (0.7%) were less commonly studied. Of the five most commonly studied disciplines, positive annual trends in odds of occurrence were noted for behavior (odds = 1.068:1, p = 0.007) and ecology (odds = 1.039, p = 0.048), and a weak positive trend was observed for parasite-oriented studies (odds = 1.032:1, p = 0.075). In contrast, odds of occurrence for distribution studies decreased with each year (odds = 0.956:1, p = 0.003). No trends were noted for management-oriented studies (odds = 1.036:1, p = 0.191).

As with disciplinary focus, research on Indiana mammals was not distributed evenly among species ($X^2 = 2168$, df = 59, $p < 0.000001$). The 10 most commonly studied mammals included six species of bats (Table 2). Neither status as a game species ($F = 0.007$, df = 1, 55, $p = 0.934$), nor current listing for conservation ($F = 0.0005$, df = 1, 55, $p = 0.983$) affected the fraction of research devoted to a species (Fig. 1). Abundant game and nongame species spanned the spectrum (Fig. 1); e.g., white-tailed deer (*Odocoileus virginianus*) and white-footed mice (*Peromyscus leucopus*) were subjects in a high fraction of publications, whereas beaver (*Castor canadensis*) and eastern moles (*Scalopus aquaticus*) were rarely studied (Table 2). Similarly, species of conservation concern ranged from relatively frequently studied (e.g., red bats, *Lasiurus borealis*) to seldom studied (star-nosed moles, *Condylura cristata*) (Table 2).

Research hot and cold spots.—The manner in which research activity on wild Indiana mammals has been distributed was first examined by jointly considering effects of subject discipline and species. Research activity varied significantly with discipline and species ($X^2 = 932$, quasi-p = 0.0002). Because some disciplines, namely, physiology, genetics, taxonomy, and paleontology, were seldom studied (< 100 occurrences), the analysis was repeated using only the remaining five most-studied disciplines; results were similar ($X^2 = 479$, quasi-p = 0.0002). For conservation-listed species, no cold spots were evident using this approach for behavior, ecology, genetics, or management (Fig. 2). Cool spots occurred for behavioral research on Allegheny woodrats (*Neotoma magister*) and ecological research on badgers (*Taxidea taxus*). Three bat species were relatively understudied vis-à-vis parasites and diseases with cold spots for Indiana myotis (*Myotis sodalis*) and tri-colored bats (*Perimyotis subflavus*), and a cool spot for little brown myotis (*M. lucifugus*) (Fig. 2).

For game species, no cold or cool spots were noted regarding management-focused research (Fig. 2). A marginally negative residual (cool spot) was noted for ecological research on raccoons (Fig. 3). Likewise, cool and cold spots were noted for parasite or disease and genetic research, respectively, on white-tailed deer. Relatively less research also was observed for survey-type studies of deer, raccoons, and tree squirrels (Fig. 3).

Nonlisted, nongame mammals exhibited the greatest number of cool and cold spots (Fig. 4). Underrepresentation was especially evident in behavioral research on southeastern shrews (*Sorex longirostris*), short-tailed shrews (*Blarina brevicauda*), least shrews (*Cryptotis parva*), deer mice (*Peromyscus maniculatus*), and southern bog lemmings (*Synaptomys cooperi*). Management-focused research was relatively deficient for masked shrews (*Sorex cinereus*), least shrews (*Cryptotis parva*), southern bog lemmings, prairie voles (*Microtus ochrogaster*), meadow jumping mice (*Zapus hudsonius*), and white-footed mice (Fig. 4). Possible deficiencies in genetics and physiology studies were observed only for big brown bats (*Eptesicus fuscus*) and eastern chipmunks (*Tamias striatus*), respectively. Neither cool nor cold spots were identified for this species group in ecology, paleontology, parasites and diseases, or taxonomy and systematics (Fig. 4).

Cool and cold spots also were assessed independently for each of the five most frequently studied disciplines. Of 22 species listed for conservation concern (Table 2), 12 received < 5% and two received 5–10% of the attention received by the best-studied species in at least one of the five most frequently studied disciplines, i.e., behavior, ecology, distribution, management, and parasites (Fig. 5). Species with at least three cool or cold spots as defined in Fig. 5 included star-nosed mole (*Condylura cristata*, all five disciplines), Rafinesque's big-eared bat (*Corynorhinus rafinesquii*, four), eastern small-footed myotis (*M. leibii*, four), swamp rabbit (*Sylvilagus aquaticus*, four), Franklin's ground squirrel (*Policocitellus franklinii*, four), American black bear (*Ursus americanus*, four), pygmy shrew (*Sorex hoyi*, four), smoky shrew (*S. fumeus*, three), least weasel (*Mustela nivalis*, three), badger (three), and plains pocket gopher (*Geomys bursarius*, three). Of 15 game species, seven received < 5% of the

Table 2.—Native Indiana mammals presented in descending order of overall fraction of publications in which they appeared (Overall), classified by relative abundance and status as game species. Abbreviations: A = abundant; C = common; SC = special concern; SE = state endangered; FT = federally threatened; FE = federally endangered; Occ = occasional.

Species	Common name	Status	Game	Overall
Myotis sodalis	Indiana myotis	SEFE	No	0.061
Peromyscus leucopus	White-footed mouse	A	No	0.056
Odocoileus virginianus	White-tailed deer	A	Yes	0.051
Eptesicus fuscus	Big brown bat	A	No	0.048
Myotis lucifugus	Little brown myotis	SE	No	0.044
Myotis septentrionalis	Northern long-eared myotis	SEFT	No	0.041
Perimyotis subflavus	Tri-colored bat	SE	No	0.040
Procyon lotor	Raccoon	A	Yes	0.039
Lasiurus borealis	Red bat	SC	No	0.035
Tamias striatus	Eastern chipmunk	A	No	0.032
Nycticeius humeralis	Evening bat	SE	No	0.029
Sciurus carolinensis	Gray squirrel	A	Yes	0.029
Peromyscus maniculatus	Deer mouse	A	No	0.029
Sciurus niger	Fox squirrel	A	Yes	0.028
Lasiurus cinereus	Hoary bat	SC	No	0.025
Blarina brevicauda	Short-tailed shrew	A	No	0.025
Microtus ochrogaster	Prairie vole	A	No	0.023
Lasionycteris noctivagans	Silver-haired bat	SC	No	0.023
Microtus pennsylvanicus	Meadow vole	A	No	0.021
Didelphis virginiana	Virginia opossum	A	Yes	0.017
Sylvilagus floridanus	Eastern cottontail	A	Yes	0.016
Tamiasciurus hudsonicus	Red squirrel	A	No	0.016
Neotoma magister	Allegheny woodrat	SE	No	0.016
Sorex cinereus	Masked shrew	A	No	0.015
Glaucomys volans	Southern flying squirrel	A	No	0.015
Canis latrans	Coyote	A	Yes	0.013
Vulpes vulpes	Red fox	C	Yes	0.013
Myotis grisescens	Gray myotis	SEFE	No	0.011
Sorex longirostris	Southeastern shrew	A	No	0.011
Zapus hudsonius	Meadow jumping mouse	C	No	0.011
Microtus pinetorum	Woodland vole	A	No	0.010
Neogale frenata	Long-tailed weasel	A	Yes	0.009
Mephitis mephitis	Striped skunk	A	Yes	0.009
Marmota monax	Woodchuck	A	No	0.009
Myotis austroriparius	Southeastern myotis	SC	No	0.009
Ictidomys tridecemlineatus	13-lined ground squirrel	A	No	0.008
Cryptotis parva	Least shrew	A	No	0.007
Synaptomys cooperi	Southern bog lemming	A	No	0.006
Urocyon cinereoargenteus	Gray fox	C	Yes	0.006
Ondatra zibethicus	Muskrat	A	Yes	0.006
Scalopus aquaticus	Eastern mole	A	No	0.006
Geomys bursarius	Plains pocket gopher	SC	No	0.005
Sorex fumeus	Smoky shrew	SC	No	0.005
Poliocitellus franklinii	Franklin's ground squirrel	SE	No	0.005
Mustela nivalis	Least weasel	SC	No	0.005
Neogale vison	Mink	A	Yes	0.005
Corynorhinus rafinesquii	Rafinesque's big-eared bat	SC	No	0.004
Reithrodontomys megalotis	Western harvest mouse	C	No	0.004
Lynx rufus	Bobcat	C	No	0.004
Sorex hoyi	Pygmy shrew	SC	No	0.004
Sylvilagus aquaticus	Swamp rabbit	SE	No	0.004
Castor canadensis	Beaver	C	Yes	0.003
Myotis leibii	Eastern small-footed myotis	SC	No	0.003
Taxidea taxus	Badger	SC	No	0.003
Lontra canadensis	River otter	C	Yes	0.002
Ursus americanus	American black bear	SC	No	0.002
Condylura cristata	Star-nosed mole	SC	No	0.002
Dasypus novemcinctus	Nine-banded armadillo	Occ	No	0.001

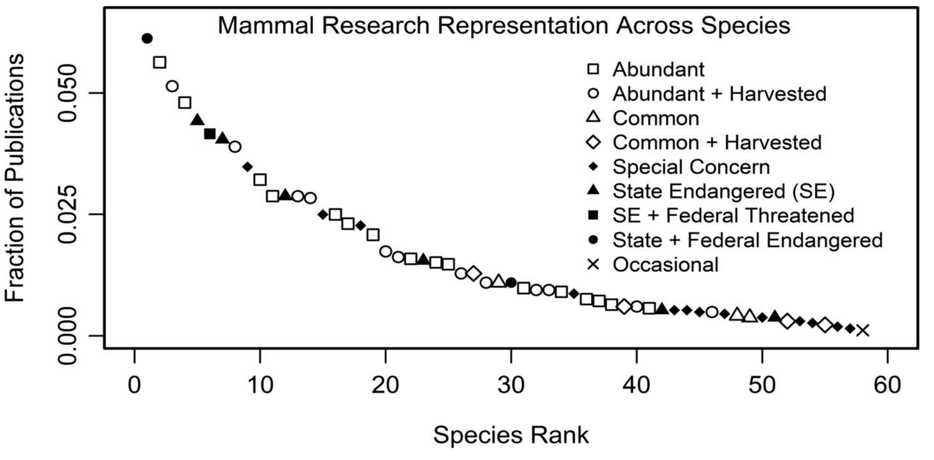

Figure 1.—Fraction of research publications on Indiana mammals in which each species occurred. Species were ranked in descending order and classified according to relative abundance and current conservation and game status. Publications were obtained from a systematic review conducted 19–21 May 2022 in Web of Science™ and additions made through 29 December 2022.

attention received by the best-studied species in at least one of these five disciplines, and all except *Didelphis virginiana* and *Canis latrans* received < 10% of the attention of the best-studied species in at least one discipline (Fig. 6). For game species, which typically are abundant and widespread geographically, exclusion of distribution studies from consideration resulted in seven species receiving < 10% of the attention given to the best-studied species in the remaining four disci-

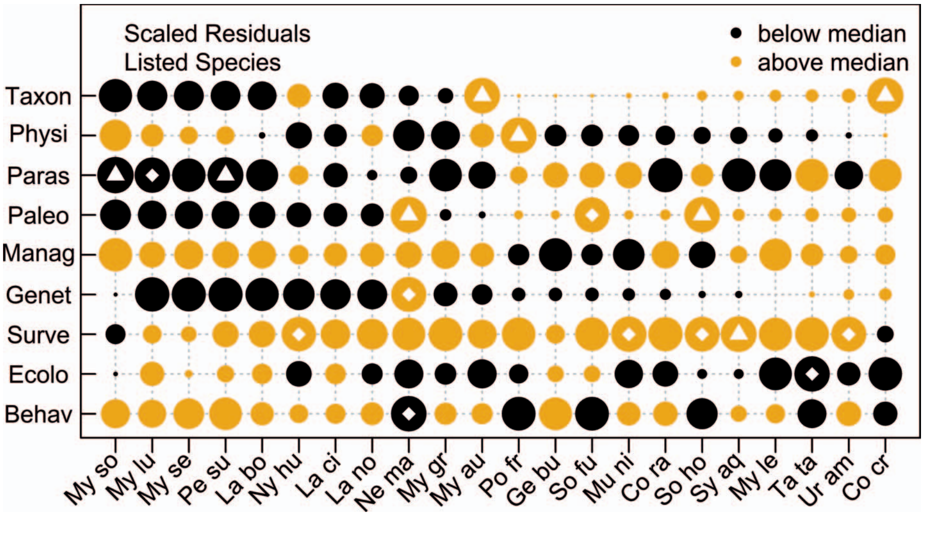

Figure 2.—Bubble map of research hot (gold) and cold (black) spots on Indiana mammals listed for conservation, classified by species and discipline. Each bubble is based on quantiles for Pearson chi-square residuals, with bubble area proportional to the focal combination's distance from the median residual value; i.e., observed combinations of discipline and species with residuals at the 50th percentile have zero area, whereas the largest bubbles occur for combinations with residuals at the 0th and 100th percentiles. White triangles depict residuals in the outer 2.5% of either tail, and white diamonds represent residuals in the outer 2.5–5% of either tail. Discipline abbreviations are the first five letters from Table 1 names. Species abbreviations are the first two letters of genus and species names from Table 2, arranged in descending order of frequency of appearance in publications.

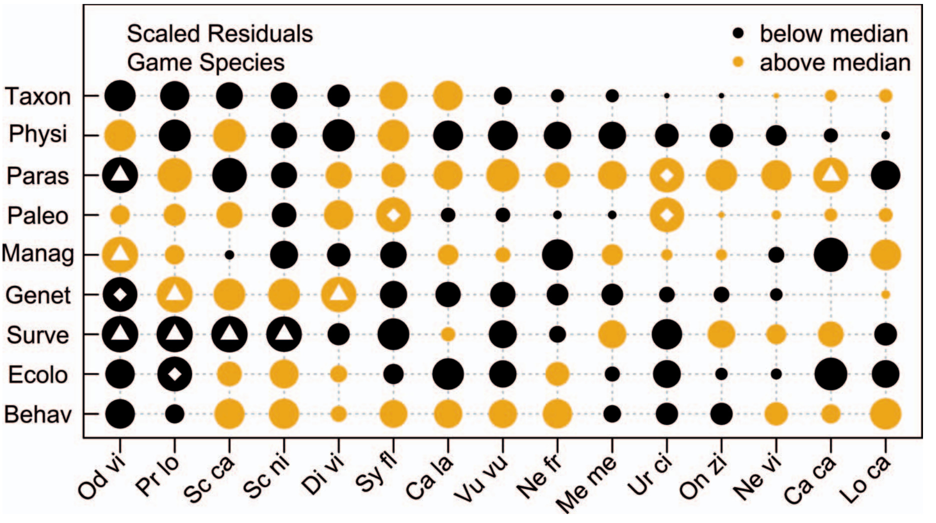

Figure 3.—Bubble map of research hot (gold) and cold (black) spots on harvestable Indiana mammals. Each bubble is based on quantiles for Pearson chi-square residuals. Explanations of symbols, axis label abbreviations and species ordering are given in Fig. 2.

plines. Five game species were broadly understudied using this approach to quantifying research inequity (Fig. 6): river otter (*Lontra canadensis*, all five disciplines), mink (*Neogale vison*, four), gray fox (*Urocyon cinereoargenteus*, four), beaver (four), and muskrat (*Ondatra zibethicus*, three). Of 21 native species classified neither as game nor listed for conservation, 11 received < 5% of the attention given to the best-studied species in at least one discipline, and three received 5–10% (Fig. 7). Seven broadly understudied species were neither harvested nor listed (Fig. 7): bobcat (*Lynx rufus*, five disciplines), nine-banded armadillo (*Dasypus novemcinctus*, five), eastern mole (*Scalopus aquaticus*, four), western harvest mouse (*Reithrodontomys megalotis*, four), southern bog lemming (three), 13-lined ground

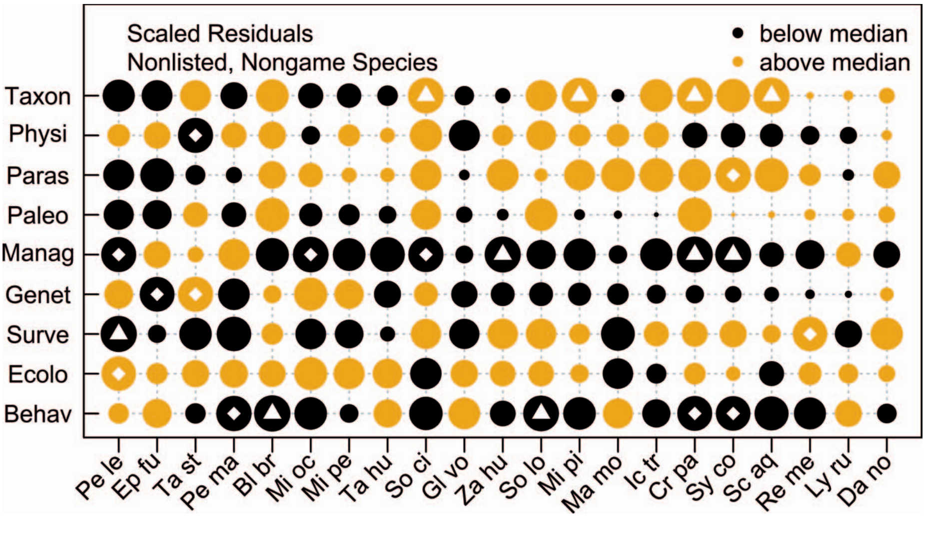

Figure 4.—Bubble map of research hot (gold) and cold (black) spots on native Indiana mammals that are neither listed nor harvested. Each bubble is based on quantiles for Pearson chi-square residuals. Explanations of symbols, axis label abbreviations and species ordering are given in Fig. 2.

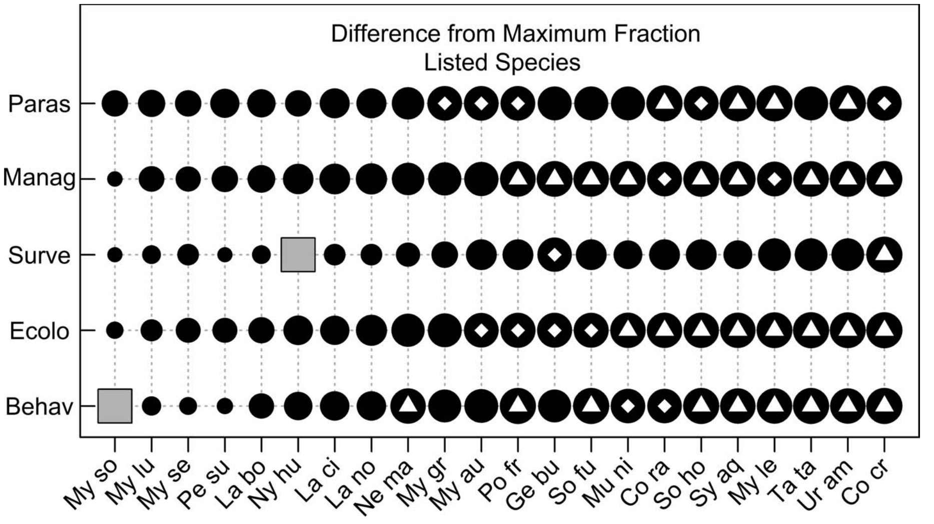

Figure 5.—Bubble map of research representation in the five most-studied disciplines for native mammals of Indiana listed for conservation. Within a discipline, circle areas are proportional to the difference between the focal and the most-studied species in that discipline; larger circles depict greater discrepancies. White triangles depict species studied < 5% as much as the most-studied species in that discipline. White diamonds represent species studied 5–10% as much as the most-studied species in the discipline. Gray squares depict the most-studied of all 58 species in each discipline. Explanations of axis label abbreviations and species ordering are given in Fig. 2.

squirrel (*Ictidomys tridecemlineatus*, three), and woodchuck (*Marmota monax*, three).

Bibliometric results.—The 714 publications on Indiana mammals represent an annual rate of 6.2 papers over the 116-year period for which results were obtained. Collectively, the publications have been cited 14,100 times according to Web of Science™, for an average

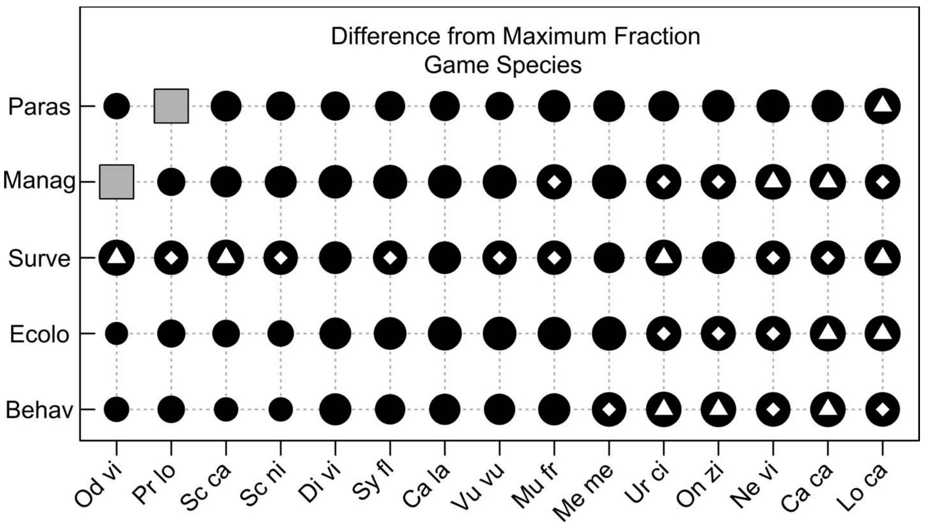

Figure 6.—Bubble map of research representation in the five most-studied disciplines for harvestable native mammals of Indiana. Within a discipline, circle areas are proportional to the difference between the focal and the most-studied species in that discipline. Explanations of axis label abbreviations and species ordering are given in Fig. 2.

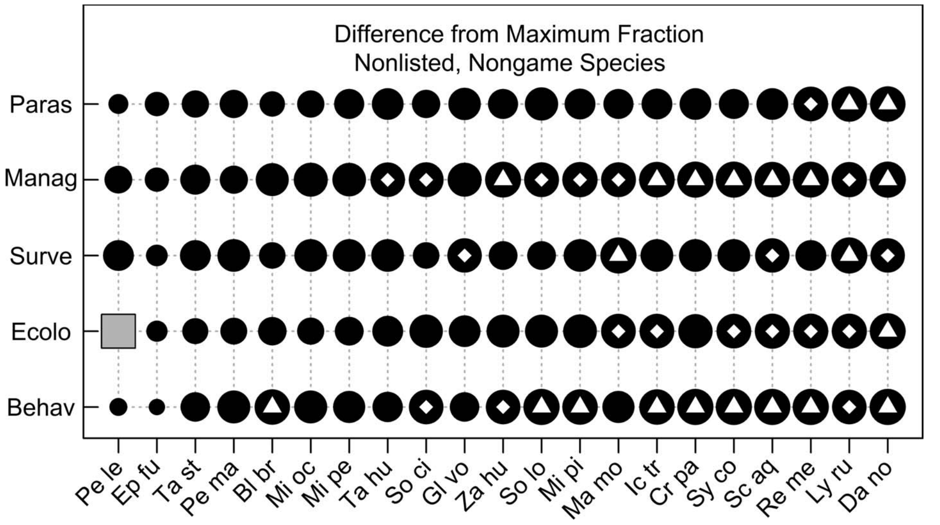

Figure 7.—Bubble map of research representation in the five most-studied disciplines for native Indiana mammals that are neither listed nor harvested. Within a discipline, circle areas are proportional to the difference between the focal and the most-studied species in that discipline. Explanations of axis label abbreviations and species ordering are given in Fig. 2.

of 19.7 citations per article. The h-index was 56, meaning 56 articles were cited at least 56 times, with an annual h-index accumulation rate, i.e., m quotient, of 0.48. The distribution of citations was strongly skewed; most publications were cited a few times (median = 7), 301 (42.2%) were cited at least 10 times, and 29 (4.1%) were cited $\geq$ 100 times (Supplemental Material). Of the 29 papers cited $\geq$ 100 times, a majority (76%) considered aspects of ecology. Taxonomically, 21 of these 29 highly cited papers (72.4%) reported results for rodents, with lower incidence for bats (24.1%) and carnivores (10.3%). Only 6 papers (0.8%) were cited $\geq$ 200 times. Of these, three focused on rodents (Gu & Swihart 2004; Krebs et al. 1969, 1973; with 565, 544, and 311 citations, respectively), one focused on bats (Whitaker 1988, 205 citations), one focused on mammalian predators (Gehring & Swihart 2003, 211 citations), and one examined Pleistocene megafauna (Gill et al. 2009, 377 citations).

A total of 1131 authors contributed to the body of scientific knowledge on Indiana mammals. Of these, 74 (6.7%) authored or co-authored $\geq$ 5 publications, and 31 (2.7%) produced $\geq$ 10 publications (Table 3). Not surprisingly, most of the former authors (81%) were affiliated with state-supported universities, led by Purdue (61%) and Indiana State (26%). Among authors with $\geq$ 5 publications, number of publications (r = 0.51, $t = 5.00$, df = 72, $p << 0.0001$), h-index (r = 0.45, $t = 4.23$, df = 72, $p = 0.00007$), and number of citations ($r = 0.36$, $t = 3.28$, df = 72, $p = 0.0016$) were positively correlated with the timespan over which active publishing occurred, and distributions of publication and citation counts were skewed toward senior researchers with decades of research on Indiana mammals. For instance, the two most highly published and widely cited authors (J.O. Whitaker, Jr. & R.K. Swihart) had publication records on Indiana mammals spanning 55 years and 27 years, respectively (Table 3). Collectively, the papers they authored or coauthored accounted for 36.4% of all publications and 40.7% of all citations. In contrast, productivity expressed as an annual rate of publication (r = -0.19, t = -1.66, df = 72, $p = 0.101$) and impact expressed as an m quotient, i.e., annual rate of h-index accumulation (r=-0.19, t=-1.65, df=72, p= 0.104) tended to be higher for authors with shorter timespans over which research was published on mammals in Indiana.

DISCUSSION

General trends.—Trends in the magnitude of published research on mammals in Indiana likely paralleled closely trends in scientific capacity at state universities and other institutions. Early research was done by a small

Table 3.—Publications, citation counts, *h*-index, and associated annual rates for each of these bibliometrics, for authors of $\geq$ 10 articles on mammals in Indiana. Years refers to the timespan over which an author published the articles. Numbered superscripts signify rankings within each column from among 1131 authors identified via Web of Science™ from 1906–2022. The top ranking is boldfaced for each metric. ISU = Indiana State University; ESI = Environmental Solutions & Innovations, Inc.; 3D = 3D Environmental Services, Inc.; IUP = Indiana University of Pennsylvania.

	Publications		Citations		*h*	*m*		
Author	Count	Rate	Count	Rate	index	quotient	Years	Affiliation
Whitaker, J.O., Jr.	**156[1]**	2.79[5]	2481[2]	43.1[4]	**27[1]**	0.47[35]	55[2]	ISU
Swihart, R.K.	101[2]	**3.61[1]**	**3262[1]**	**118.6[1]**	**27[1]**	0.98[3]	27[16]	Purdue University
Rhodes, O.E., Jr.	49[3]	3.50[3]	940[6]	60.6[2]	18[3]	**1.16[1]**	13[49]	Purdue University
Beasley, J.C.	35[4]	2.19[7]	719[7]	46.4[3]	16[4]	1.03[2]	15[44]	Purdue University
Brack, V., Jr.	34[5]	0.87[653]	551[12]	13.9[32]	12[5]	0.30[74]	38[4]	ESI, 3D, ISU, Purdue
Johnson, S.A.	30[6]	0.91[651]	254[38]	7.8[80]	10[10]	0.31[72]	32[9]	DNR Wildlife
Sparks, Dale W.	29[7]	1.38[36]	480[15]	22.3[16]	12[5]	0.56[29]	20[29]	ISU, ESI
Mumford, R.E.	25[8]	0.78[663]	179[50]	2.6[160]	8[21]	0.12[271]	31[10]	Purdue University
Zollner, P.A.	24[9]	0.92[649]	493[14]	19.3[22]	10[10]	0.39[57]	25[21]	ISU, Purdue
Cope, J.B.	22[10]	0.37[744]	276[34]	3.8[120]	7[23]	0.10[303]	**58[1]**	Earlham College
Weeks, H.P., Jr.	21[11]	0.72[671]	576[10]	12.4[36]	11[8]	0.24[112]	28[14]	Purdue University
Smyser, T.J.	20[12]	1.43[35]	236[41]	16.3[26]	10[10]	0.69[10]	13[49]	Purdue University
Kazacos, K.R.	17[13]	0.43[731]	440[18]	9.7[62]	12[5]	0.26[104]	39[3]	Purdue University
Kellner, K.F.	16[14]	1.45[34]	204[45]	15.1[29]	9[15]	0.67[11]	10[66]	Purdue University
Kirkpatrick, C.M.	16[14]	0.43[724]	343[28]	4.3[111]	10[10]	0.13[244]	36[6]	Purdue University
O'Keefe, J.M.	16[14]	1.60[27]	189[47]	19.9[18]	6[32]	0.63[26]	9[70]	ISU, U. Illinois
Page, L.K.	16[14]	0.84[657]	391[21]	16.0[27]	11[8]	0.45[39]	18[34]	Purdue, Wheaton
Dharmarajan, G.	15[18]	1.50[28]	247[39]	15.9[28]	10[10]	0.64[25]	9[70]	Purdue University
Richards, R.L.	14[19]	0.41[733]	84[95]	1.7[247]	4[49]	0.08[363]	33[7]	IN State Museum
Duchamp, J.E.	12[20]	0.63[694]	447[17]	22.9[15]	9[15]	0.46[36]	18[34]	ISU, Purdue, IUP
Flaherty, E.A.	12[20]	1.71[25]	53[135]	8.2[74]	5[40]	0.77[7]	6[97]	Purdue University
Boyles, J.G.	11[22]	0.92[650]	321[29]	19.5[21]	7[22]	0.42[41]	11[60]	ISU
Clay, K.	11[22]	0.69[672]	529[13]	23.5[13]	9[15]	0.40[42]	15[44]	Indiana University
Haulton, G.S.	11[22]	1.22[43]	59[126]	6.9[86]	6[32]	0.71[9]	8[78]	DNR Forestry
Krohne, D.T.	11[22]	0.69[672]	300[32]	7.8[81]	9[15]	0.23[115]	15[44]	Wabash College
Lyon, M.W., Jr.	11[22]	0.55[708]	25[236]	0.3[543]	3[67]	0.03[577]	19[32]	South Bend Clinic
Olson, Z.H.	11[22]	1.10[47]	247[39]	19.8[20]	7[23]	0.56[28]	9[70]	Purdue University
Fike, J.A.	10[28]	0.83[658]	119[67]	7.7[83]	7[23]	0.45[38]	11[60]	Purdue University
Jenkins, M.A.	10[28]	0.45[749]	114[69]	5.3[98]	6[32]	0.28[100]	21[28]	Purdue University
Lichti, N.I.	10[28]	1.67[26]	205[44]	21.6[17]	7[23]	0.74[8]	5[118]	Purdue University
Ritzi, C.M.	10[28]	1.11[46]	209[43]	10.2[57]	8[21]	0.39[58]	8[78]	ISU, Sul Ross State

number of pioneers including Walter Hahn (e.g., Hahn 1906a, 1906b) and Marcus W. Lyon, Jr. (e.g., Lyon 1923, 1932), with significant capacity added in the mid-20th century by faculty at state colleges and universities, notably Charles Kirkpatrick, Russell Mumford, James Cope, and John Whitaker, Jr. (Table 3). Early studies tended to be descriptive and qualitative, with a focus on range records, species lists, and natural history observations. The late 1960s marked the beginning of a gradual transition to research that relied more on experimental and comparative approaches to test hypotheses, led by the groundbreaking work of Charles Krebs and his students at Indiana University on *Microtus* population dynamics (Krebs et al. 1969, 1973) and genetics (Tamarin & Krebs 1969; Gaines & Krebs 1971), and continued with other taxa in studies as varied as subterranean foraging behavior of plains pocket gophers (Andersen 1988), energetics of gray squirrels (Byman et al. 1988), and sensory ecology of white-footed mice (Zollner & Lima 1997). An even more pronounced transition began in the 1980s, namely, a shift in composition of ecological research from predominantly natural history observations to studies of species-environment relationships.

Rapid technological advances in at least three areas also influenced mammalogical research trends in the 21st century. First, increases in computing power and advances in applied statistics led to increasingly sophisticated quantitative analysis methods (e.g., Moore & Swihart 2005; Clement et al. 2015; Jones et al. 2022). Second, more affordable and precise genetic tools broadened the range of tractable questions in mammalian biology (e.g., Beasley et al. 2010; Smyser et al. 2012; LaBonte & Woeste 2018). Finally, enhanced resolution and availability of remote sensing platforms and geographic information systems have facilitated larger-scale and longer-term research on species-environment associations (Pauli et al. 2015; Jones et al. 2022).

Indiana mammals differ greatly in form and function. Likewise, researchers exhibit a diverse set of interests. Not surprisingly, then, disciplines and species were unequally represented in the research record of Indiana mammals. From a disciplinary perspective, the preponderance of ecological and management-oriented research was expected, as ecology encompasses a vast array of organism-environment interactions with practical implications, and statutory and funding considerations often prioritize studies tied to management of game species and conservation of rare species. Parasite and disease research likely gained greater attention in Indiana than elsewhere because of the interests of John Whitaker and coworkers in mammalian ectoparasites (e.g., Whitaker 1973; Whitaker & Goff 1979; Fain & Whitaker 1988), and Kevin Kazacos and coworkers in intestinal parasites (e.g., Kazacos 1982; Sheppard & Kazacos 1997; Page et al. 2016).

From a taxonomic perspective, a minority of species have attracted the majority of research attention. As a group, bats have attracted the greatest attention, perhaps because of their unique combination of sensory and physiological traits coupled with their imperiled status. Game species, including deer, tree squirrels, and raccoons, also have received considerable research attention, presumably because of their management value. White-footed mice and eastern chipmunks have been subjects of extensive study, often as models for ecological processes (e.g., Krohne & Hoch 1999) or barometers of anthropogenic impacts on ecosystems (e.g., Nupp & Swihart 1998; Mossman & Waser 2001).

Mapping cold spots.—Recognizing the factors contributing to popular study species is important, but arguably greater value lies in identifying understudied discipline × species combinations, as these represent potential cold spots in knowledge that future research could address. Two approaches were used to assess inequities in research attention, and they offer different perspectives. The first approach to assessing research shortcomings relied on inspection of chi-squared residuals computed under a null hypothesis of homogeneous proportions across species and disciplines considered jointly (Figs. 2–4). So, for example, less research was devoted to the study of deer mouse behavior than expected under a null hypothesis of equitable apportionment of effort, which was derived from the frequency with which behavior and deer mice were studied overall. Similar cool and cold spots in behavioral research were noted for least, southeastern and short-tailed shrews, secretive species for which direct observation is difficult. Some cold spots identified from residuals likely merit more consideration than others; e.g., the cool spot for badger ecology (Fig. 2) reflects a sparse research record in Indiana and considerable uncertainty associated with the species' ecology. In contrast, the cold spot for raccoon ecology (Fig. 3) likely is a consequence of the high level of attention given to other aspects of this relatively well-studied species' biology, especially genetics. On a positive note, no management cold spots were identified for either harvested or listed species; only the cool or cold spot for prairie voles and southern bog lemmings (Fig. 4) might suggest greater need for attention. Parasite and disease cold spots occurred exclusively for well-studied species including deer, gray squirrels, tri-colored bats, and Indiana and little brown myotis, reflecting less attention given to disease and disease vectors compared to management, ecology, behavior, and (for bats) surveys.

When considering each discipline in isolation, numerous species received less than 10% of the attention relative to the most frequently studied species (Figs. 5–7). For brevity, the following focuses on the disciplines of ecology and management. Ten species of conservation concern were understudied in both ecology and management according to their relative representation in publications (Fig. 5). Several of these species are cryptic and difficult to sample using traditional methods including smoky and pygmy shrews, star-nosed mole, and least weasel. Future studies of these species could benefit from rapidly developing non-invasive sampling techniques, such as environmental DNA (Bohmann et al. 2014), acoustic detection (Zsebők et al. 2015), and camera trapping (Delisle et al. 2021). Evidence of declining weasel populations across North America over the past 60 years (Jachowski et al. 2021), coupled with the paucity of information on least weasels in Indiana, suggest that prioritizing research on weasels could be helpful.

Five game species met the criterion for being understudied in both disciplines (Fig. 6), namely gray fox, mink, muskrat, beaver, and river otter. IDNR biologists recognized the understudied status of gray fox and, in response to declining population levels, initiated ecological research in 2020 to identify possible causes of decline (https://www.wildlifeecology.org/grayfox_indiana.html). Population-level research on muskrat is needed for similar reasons, as widespread population declines have been documented throughout much of the species' range (Ahlers & Heske 2017; Sadowski & Bowman 2021). In contrast, river otter reintroductions began in 1995, and the species' $>$ 50-year absence from the state likely contributed to its relative lack of study. Otters have spread throughout the state and, together with beaver, may benefit from future studies to manage conflicts with humans in increasingly modified landscapes.

A few understudied nongame, nonlisted species also merit mention (Fig. 7). Bobcats appear to have recovered from a population nadir in the mid-1990s, but detailed study has been restricted largely to a core population in southcentral Indiana (Johnson et al. 2010). Given the traditional classification of bobcat as a game species, future research, possibly on other subpopulations, may be useful. Two small mammals, eastern mole and southern bog lemming, have received relatively little attention from researchers and thus deserve closer inspection. Like beavers, eastern moles are ecosystem engineers that may play outsized roles in enhancing community diversity (Yeakel et al. 2020) and thus could be important in assembly processes associated with non-equilibrium communities of (mostly) nonnative earthworms. Southern bog lemmings are enigmatic and poorly understood. Despite a sizable geographic distribution in North America, little is known about the species' reproduction, its digestive physiology is poorly understood (notwithstanding a uniquely shaped cecum and production of rounded, bright green feces that differentiate it from other arvicoline rodents including voles in Indiana), and its habitat selection is complex and may be tied to the local abundance of behaviorally dominant voles (Rose & Linzey 2021).

Researcher performance and capacity.—Indiana has a rich history of mammalogical research, and an authorship count (1131) that exceeds the total publication count (714) speaks volumes about the breadth of commitment to acquire knowledge of mammals. Somewhat paradoxically, though, scientific capacity generally was modest for most of the 20th century. During this period, research effort on Indiana mammals was led largely by a handful of scientists with permanent appointments. During the last quarter century or so, permanent research capacity has increased, thanks to greater emphasis on mammalogical research in IDNR and expanded numbers of research-active faculty at colleges and universities. Importantly, mammal research in Indiana has become demonstrably more collaborative; witness the increase in mean ($\pm$ SD) number of authors on papers, from 1.0 $\pm$ 0 before 1930 (n = 8 papers) to 2.1 $\pm$ 1.0 in the 1970s (n = 77), and finally 4.2 $\pm$ 2.9 from 2020–2022 (n = 44). The latter value is technically too low, as it was computed after excluding two papers with $>$ 150 authors each that reported results from coordinated national camera trap surveys. Collaboration has been fueled by increased involvement of undergraduate student researchers and postdoctoral scientists at universities, larger-scale and longer-term projects requiring multiple investigators, and increased ease coordinating large team efforts and sharing data in the internet age. Nonetheless, maintaining enhanced capacity requires constant recruitment because the vast majority of contributors to mammalogical research in Indiana engage temporarily; 73.4% published in a single year, and 81.4% published over timespans typical of graduate study, i.e., $\leq$ 4 years. Many of these temporary Indiana researchers go on to conduct mammalogical research in other states and countries, thereby broadening the impact of Indiana training on our understanding of mammals.

Top contributors to research on Indiana mammals, at least as measured by bibliometrics (Table 3), exhibit some common features. Quantitatively, their research lifespans were uniformly longer than most contributors, averaging 21 years (range: 5–58 years). Greater longevity has enabled many top contributors to develop research programs, rather than individual projects, and to specialize with respect to particular taxa, topic areas, methods, or a combination of these. In addition, research longevity can beget more well-developed collaborative networks capable of fostering further improvements in productivity and impact.

The list of top contributors also highlights a less flattering feature of mammal research in Indiana, namely, a legacy of privilege and exclusion. Specifically, 26 of 31 scientists listed in Table 3 are white males, with only four females and one person of color (derived from personal observation and knowledge of authors). Moreover, increased diversity of the group has occurred only over the last 2 decades. Lack of diversity can hamper collective creativity and scientific quality by unduly narrowing the perspectives, approaches, and mindsets brought to science and its interactions with society (references in Graves et al. 2022). Although the recent uptick in diversity is modestly encouraging, exclusion of historically underrepresented groups has stubbornly persisted in life science disciplines (e.g., Ahmadia et al. 2021) and becomes more pronounced with career progression in evolution (Rushworth et al. 2021) and natural resources (Swihart et al. 2016, 2018). Undergraduate enrollment in environmental science is increasingly diverse and > 50% female (Bal et al. 2022), thus, the persistence of underrepresentation among top contributors implicates bias and institutional barriers as challenges to retention. Fostering a more inclusive, equitable, and representative population of mammalogical researchers will necessitate changes to the traditional research culture and climate by adopting practices that explicitly value diversity and support work-life balance (Lerman et al. 2021; O'Connell & McKinnon 2021), broaden norms of success and achievement beyond the inherent limitations of simple metrics (Swihart et al. 2016, 2018), and encourage collaboration over competition (Graves et al. 2022). Building a legacy of equity and inclusion in mammal research, in Indiana and globally, is important to future advances in knowledge and is long overdue.

Caveats.—At least four limitations of the review merit mention. First, although the Web of Science™ collection is huge, it does not include publications before 1900 or all possible sources. Thus, some articles were undoubtedly missed. To partly offset this constraint, members of the IDNR and its technical advisory committee on mammals graciously augmented the 714 articles included in the systematic review with 77 pre-1900 articles and "gray literature" IDNR reports not covered by Web of Science™. These 791 references are available online as a searchable database (Supplemental Material). Second, the broad disciplinary categories used in the review, while able to reflect general patterns, are too coarse to offer detailed analysis of specific research needs. For instance, a cold spot in ecological research offers no information on the identity of the underrepresented branch(es) within the field of ecology. Inferences drawn from the review should thus be treated as starting points for closer inspection and determination of research needs. Third, abundance and conservation status of several species have changed since 1906, complicating attempts to interpret results derived over the entire period of the review. In particular, little brown myotis and tri-colored bats formerly were common in Indiana (Whitaker & Mumford 2009); precipitous declines are recent and coincident with the spread of white-nose syndrome. Finally, the review's focus on studies conducted in Indiana constrained its scope geographically. Conducting a review of research done across the entire range of each of Indiana's species was not feasible. Still, completion of similar reviews in neighboring states would provide a valuable regional perspective and an opportunity for meta-analysis as a further aid to research planning.

A resource for the future.—Confucius advised to "study the past if you would define the future." Scientific knowledge tends to advance incrementally, with prior findings informing future discovery. Hence, a refined understanding of earlier accomplishments is crucial to effective scientific progress. As an aid to those planning future research on Indiana mammals, the searchable database and digital copies of associated articles are maintained on the Purdue University Research Repository for members of the IDNR technical advisory committee on mammals. Creating a single source for articles that have accumulated for > 2 centuries and are scattered among > 150 outlets should make prior research on Indiana mammals more accessible and assist those planning future studies.

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